IMPACT AND CRATERING PROCESSES ON ASTEROIDS, SATELLITES, AND PLANETS

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We have developed and applied a new model for scaling the outcome of catastrophic collisions from laboratory-scale experiments to large bodies where gravitational binding is dominant. This algorithm includes a pressure-dependent impact strength (see Davis et al, Icarus 62, 1985 for definition of terms) which predicts that large asteroids behave as intrinsically strong objects due to compressive loading of overburden throughout their interiors. For small bodies ($<$ few kilometers diameter), where the gravitational loading is negligible, this model assumes that the impact strength is independent of size. There was considerable discussion of scaling laws for disruption at the August 1985 workshop in Pisa where Dr. Davis presented these results (see Davis, Mem. Soc. Astron. Ital. Vol. 57, No. 1, 1986). The pressure strengthening impact strength model was viewed as physically quite plausible; however, it was argued that the impact strength should decrease with increasing size in the size range where gravitational compression is negligible.

Numerical simulations of asteroid collisional evolution, which investigate possible initial assteroid mass distributions at the time their collisional speeds were pumped up to 5 km/s, are also described by Davis et al (Icarus 62, 1985). Successful candidate intial populations must satisfy three constraints: (a) they must evolve to the present observed size distribution, (b) Vesta must not be shattered in order to preserve its observed nearly-homogeneous basaltic crust, and (c) there must be enough collisional evolution to produce at least the observed number of Hirayama families. We considered various hypothetical initial population distributions, and found that a very steep size distribution, containing very few large bodies but numerous small bodies totalling only several times the current belt mass, best satisfied all constraints. This result implies that the asteroid region already was depleted in mass relative to the terrestrial planet region by the time velocities were stirred up to ~5 km/s.

We also calculate the number of asteroids that are formed by different mechanisms, e.g. unshattered original survivors, gravitationally bound rubble piles, fragments from the collisional disruption of larger bodies, etc. We then relate these distributions to statistical properties of the observed asteroid population that may be influenced by asteroid physical states. For example, intermediate size asteroids (100-200 km diameter) are the sizes at which gravitationally bound rubble piles should be most abundant. This is also the size range at which Zappala et al. (Icarus 59, 261, 1984) found observational evidence for large amplitude lightcurves among rapidly rotating asteroids. One interpretation is that the gravitationally bound rubble piles relax to quasi-equilibrium shapes. Other relationships between observable properties and the calculated physical state are being investigated.

The idea that rotational properties of asteroids constrain their physical nature and collisional history has been stimulated by demonstrations

that the mean spin period varies with size and taxonomic class (Farinella et al. Astron. Astrophys. 104, 159, 1981; Dermott et al., Icarus 57, 14 1984). These studies show that intermediate-sized asteroids ($20 < D < 200$ km) rotate more slowly, on average, than do smaller and larger ones. Dobrovolskis and Burns (Icarus 57, 464, 1984) interpret this as due to "angular momentum drain" (i.e., braking by preferential escape of impact ejecta in the direction of rotation). While this mechanism is qualitatively plausible, many quantitative details remain to be worked out. Their formalism treats all impacts as crater-forming events, with ejecta derived from the surface at the impact point. From the observed size distribution, it is known that most of the mass and angular momentum impacting an asteroid is delivered in the few largest events that occur in its lifetime. Moreover, our collisional simulations show that most asteroids smaller than ~150 km either have been shattered by major impacts on a much larger scale than crater-forming events, or are fragments from the disruption of larger parent bodies. Thus, it may be premature to draw quantitative conclusions as to asteroid properties and collisional history based on this model. Still, we note that Farinella et al. conclude that the observed angular momenta of large asteroids is compatible with only a moderate depletion, about a factor of five, of the original mass of the belt, in substantial agreement with our own results based on the observed size distribution.

It is accepted by most workers that Hirayama families are formed by major asteroid collisions. The collision shatters and disrupts both target and projectile producing fragments moving at velocities which enable them to escape their mutual gravitational binding and to follow their own orbits about the sun. Even the small mass belt favored by Davis et al. (1985) for the initial asteroid belt would have resulted in catastrophic disruption of around 150 bodies larger than 100 km size over solar system history. Yet there are nowhere near that number of Hirayama families that make sense geochemically. Hirayama families, if created by catastrophic disruption, may have a lifetime considerably shorter than the age of the solar system. There was catastrophic disruption of 10-12 bodies larger than 100 km in size in the last billion years according to the favored scenario of Davis et al. (1985). This number is in reasonably good agreement with the ten families having parent bodies $\gtrsim 90$ km in size described by Gradie et al. (in Asteroids, T. Gehrels, ed., p. 359, 1979). This suggests that Hirayama families, if of collisional origin, might be recognizable only for times much less than the age of the solar system.

Dr. Chapman gave a presentation at the Pisa workshop on several issues in which observational properties of asteroids (chiefly those relating to composition) have a bearing on collisional evolution. Although a major focus of Chapman's discussion (see Chapman, Mem. Soc. Astron. Ital. Vol. 57, No. 1, 1986) was Hirayama families, he also pointed out a major problem with the identification of S- and M-type asteroids as the collisionally stripped cores of differentiated parent bodies, if collisional evolution has been modest. In addition, olivine-rich asteroids (which should be observed in abundance as fragments of the mantle material of these parent bodies) are, in fact, extremely rare in the belt.

Chapman has been examining databases on the compositions of Hirayama family members to see if they "make sense" as collisional products. Using

the 8-color survey, augmented by other spectrophotometric and radiometric databases, Chapman has been investigating whether members of 60 families (as assigned by Williams and by Kozai) show compositional distributions different from the "background" expected at the family's semi-major axis (based on the Gradie/Tedesco/Bell plots of distributions of taxonomic classes with a). He has also addressed the question of whether families that do seem to be significant in that sense make cosmochemical sense, according to adopted models for parent-body interiors. Tentative conclusions are that 45 of the 60 families are "not real", by Chapman's criteria. Half are due simply to poor statistics. But many are random collections like the background, perhaps grouped by unknown dynamical processes (or separated into apparent groups by unknown dynamical gaps). Kozai's families, in particular, seem to be too large and lacking in reality. Eleven of the 60 families studied are "real". Half of these are of homogeneous composition, implying the break-up of an undifferentiated parent body; several of these families are the well-known populous families (e.g. Themis, Koronis). The other half are problems, in the sense that they do not seem to make cosmochemical sense (these include Eos, Nysa, Ceres, and Budrosa). Preliminary results were presented at the autumn 1986 meeting of the Meteoritical Society; a paper is in preparation.

Drs. Chapman, Weidenschilling, and Davis, in response to referee's comments, have revised their manuscript prepared in collaboration with M. Leake, about the cratering history of the planet Mercury. They suggest an alternative history of Mercury possibly involving a population of intra-Mercurian bodies ("vulcanoids"); revised results were presented at the Mercury Conference held in Tucson, Arizona in August, 1986.

Chapman and McKinnon's lengthy chapter on cratering of planetary satellites for the Natural Satellites book has now appeared. It contains a thorough review of cratering physics, with particular application to icy satellites, prepared chiefly by McKinnon. It also contains Chapman's critical review of cratering statistics on the various planetary satellites, as well as on the terrestrial bodies. The authors apply crater-scaling relationships developed in the first part of the chapter in order to make inferences about the projectile populations responsible for cratering the planets and satellites throughout ancient and modern epochs. Chapman and McKinnon conclude that there are 4 (possibly 5) distinct projectile populations implied by the observed crater distributions. However, no good links have been found connectin different source populations either spatially (e.g. comets for the late heavy bombardment and more recent cratering in the inner solar system with the Ganymede/Callisto population in the outer solar system) or temporally, (comets for both the present cratering rate and the earlier heavy bombardment in the inner solar system). With no physical or temporal connection betwen the inner and outer solar system, there is no basis for estimating -- even crudely -- the cratering chronologies for the satellites of Jupiter and Saturn. More recently, Chapman and McKinnon, have been investigating the connections between their scenario and the crater populations of the Uranian satellites, recently imaged by Voyager (see McKinnon and Chapman, Eos Vol. 66, No. 46, 1985).